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foam for frost protection of crops

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SUMMARY

Nontoxic protein-based fire-fighting foam has been developed for protection of row-crop plantings of tomatoes and strawberries against overnight frosts. It can be applied by both stationary and mobile equipment.

Blankets or canopies of foam, varying in thickness from 1 to 3 inches (2.5 to 7.5 cm), applied in the late afternoon persisted throughout the frost periods of the night and during the early morning of the following day. The foam blankets provided protective insulation against radiative and advective cooling of tomatoes when temperatures below freezing continued for 12 hours and fell as low as 25°F (-4°C) for 6 hours. The foam is very light in weight, completely nontoxic to plants, and spontaneously dispersible 24 to 48 hours after application. Seedling and mature tomatoes and flowering strawberries emerged, survived, and fruited after a succession of four to eight applications of foam. After dispersal, the slight residue of foam left on foliage or scattered on fruit caused little discoloration or contamination, and was soon dissipated by water or sometimes by rain. The foam has been judged by the Food and Drug Directorate of the Department of National Health and Welfare to be free of potentially toxic ingredients.

Applications of foam permit earlier spring planting of tomatoes and reduce the risk of frost damage to the maturing crop in the fall. Extension of the use of foam to other crops, such as tobacco, melons, peppers, cranberries, and possibly grapes is also foreseen. The foam concentrate is now available and a variety of mobile units for experimental application can be obtained. As commercial production of the units is also under development, foam application will become available to farmers and growers generally.

INTRODUCTION

The suggestion that protein-derived fire-fighting foam might be used for the protection of plants against frost was first published in 1967 (6). The experiments that prompted this suggestion were preliminary and included only freezing tests with a few potted tomato and coleus plants totally submerged in the foam. This foam incorporated a special formulation manufactured by Laurentian Concentrates Ltd., Ottawa, Ontario. The remarkable insulation displayed by the foam, the apparent absence of toxicity, and the spontaneous dispersal without appreciable residue led us to suggest that frost protection of plants with foam was worth further investigation (6). For practical utilization, however, the chief problem was the low stability of the foam. In these first tests, the best preparations of commercial foam collapsed 4 to 5 hours after application. This meant that if early morning frost was expected, the foam would have to be applied late in the night, and if frost continued for many hours, the foam would not last long enough to save the crop from freezing.

The favorable response to our publication showed that our conviction as to the possibility of the use of foam for frost protection was shared by others. More significantly, this response also informed us of similar experiments in progress elsewhere. We learned, for example, that J.L. Chesness and his group at Louisiana State University (1, 2) were actively engaged in the study of the engineering aspects of frost protection with detergent-based foams. We also learned from C.B. Shear and H.L. Barrows of the United States Department of Agriculture that this department had entertained the idea of foam protection since 1953 and they sent a copy of their then unpublished report on various detergent and gelatin foams (5). Chemical Abstracts (7) reported a patent, issued in 1959 to Dow Chemical Company, for a method of protecting plants against frost with saponin and methyl cellulose foams. We did not find, however, any report describing the practical application of these foams to the protection of crop plants in the field that had been published before ours. Since then, Dean A. Eggert of Purdue University has described how strawberry blossoms may be protected with detergent foams (4).

Encouraged by the interest and activity of other workers, we decided to make every effort to improve the stability of the foams. The cooperating company began work on the development of a stable foam. By the fall of 1967, the company had prepared a satisfactory concentrate. Meanwhile, construction of a stationary apparatus that generated large quantities of foam enabled tests to be made on row crops for the first time. A severe frost provided the necessary condition to test the insulative properties of the foam and the results were most satisfying. Vast improvement in the stability of the foam had been achieved without the loss of insulation value.

It was now certain that if a method could be found for applying foam swiftly and economically on large acreages, protection from frost could become a practical reality. The company therefore turned its attention to developing an experimental mobile machine for applying foam, and produced two modifications of such a machine. Both machines, and various combinations of nozzles fitted to them, were tested in the field, where they gave rapid and complete coverage to row plantings under varying climatic conditions. The machines also made it possible to enlarge the scope and variety of the tests, so that problems of toxicity, stability, and insulation could be studied in more practical detail. Tests were performed on both seedling and mature tomatoes and on strawberry plantings in blossom and fruit. The results demonstrated clearly the feasibility of machine application of stable foam to crop plantings and further confirmed our confidence in such foams for frost protection.

The present paper is the first scientific report of these experiments and findings and of the successful manual and machine application of stable protein-based fire-fighting foam for the protection of crop plantings against frost. On the basis of the findings contained in this report, commercial development of foam for frost protection has already begun. It is hoped that this report will lead to large operations in both experimental stations and commercial establishments and that it will bring this method of protection to the attention of and use by farmers and growers.

MATERIAL AND EQUIPMENT

Many aspects of the methods used are presented in the section headed Results. It is sufficient to indicate here the locale and time of the experiments and to describe the broad features of the mechanical procedures employed. Also, since the various forms of apparatus and equipment used in these operations have, in fact, undergone radical improvement and modification since then, no attempt will be made to present the details of their construction and design. The machines must be considered to be only prototypes at this time.

All experiments were performed on rows of tomato and strawberry breeding material located in experimental field plots at Ottawa. For the experiments, which took place in October 1967, only stationary equipment and manual application were employed. Subsequent experiments in the spring, summer, and fall of 1968 were done almost entirely with mobile units.

The solutions from which the foam was generated were prepared by diluting 1 gallon (5 litres) of the special protein-hydrolysate concentrate with 20 gallons (100 litres) of water. The concentrate is now labeled by the manufacturer as Agrifoam. The diluted solutions were stored in stationary and mobile oil drums or tanks of various sizes, from which they were pumped or forced by air pressure to the foam generators.

Stationary Equipment

The stationary equipment for generating and dispersing the foam was improvised from: a 50-gallon (230-litre) oil drum, a tank of compressed air, lengths of 2-inch (5-cm) fire hose, a T-shaped cast-iron joint housing special devices to facilitate agitation and mixing of air and foam solution, and various airflow and pressure gauges. Diluted foam concentrate prepared and contained in an oil drum was forced, by compressed air, into the T-shaped joint where, by being mixed and agitated by compressed air, it expanded into a fine foam which could be ejected through a fan-shaped nozzle on the end of a fire hose (Figure 1). The degree of expansion, and the rate of delivery, of the foam at the outlet was controlled by regulating the air pressure and the rate of fluid flow in the lines. The most satisfactory expansion proved to be about 30:1, at which ratio 50 gallons (230 litres) of water-diluted concentrate produced 1,500 gallons (7,000 litres) of foam. With an air pressure of 35 pounds per square inch (psi) (2.4 kg/cm^2), about 90 gallons (400 litres) of foam per minute could be generated and delivered at the nozzle outlet. This rate of generation and delivery permitted three 50-foot (15-m) rows of tomatoes, each row 36 inches (90 cm) wide, to be completely covered in half an hour with multiple ribbons of foam 2 to 3 inches (5 to 7.5 cm) thick (Figure 2).

Compressed air was not utilized in the large mobile equipment; but, instead, pressure was produced by an air blower and fluid pressure by a centrifugal fluid pump. However, it is expected that, because of the fine control of foam expansion achieved by use of compressed air, this type of air will subsequently be used in the smaller mobile units.

Mobile Equipment

Two types of mobile units were built. The first one used a tractor-drawn 200-gallon (900-litre) tank trailer adapted from a commercially available sprayer (Figure 3). The trailer was fitted with an air blower and centrifugal fluid pump, each powered by a separate gas motor. Air coming from the blowers at 10 psi (0.68 kg/cm^2) and as much as 100 cubic feet per minute (cfm) (2,800 litres/min) and solution ejected from the tank by the centrifugal pump were admixed and agitated in chambers filled with special devices to form a foam of expansion at 30:1. The foam was then delivered forcibly under the combined air and fluid pressure through the rigid piping and the flexible hoses to nozzle outlets suspended from the rear of the trailer. Air pressure and rate of fluid flow regulated by valves and gauges on the tractor permitted control of the degree of expansion and rate of generation of the foam.

Improvements suggested by experience with the first mobile unit were now incorporated into the second unit. The second unit also used a tractor-drawn trailer; but the tank had a 400-gallon (1,800-litre) capacity and the air blower and liquid pump were tractor driven (Figure 4). The trailer was fitted on each side with a bank

of three nozzle applicators clamped to rods that could be hydraulically adjusted to different levels above the ground by the tractor operator. Two banks of applicators supplied foam coverage simultaneously to two rows of plantings, and the location of the banks at a position between the trailer and the tractor permitted both application of the foam and alignment of the tractor. At the same time, applicators could be viewed and controlled by the tractor operator as the tractor moved between the rows. Also at the same time, the rate of fluid flow and air pressure could be regulated to control the degree of expansion and rate of generation of the foam. The blower was made to operate at 15 psi (1 kg/cm²) and it had a capacity of up to 400 cfm (11,000 litres/min). Foam could be generated at a rate of 120 gallons per minute (gpm) (550 litres/min) from each of the nozzle heads, of which there were six altogether in the two banks. This rate of generation permitted approximately 6,600 feet (2,000 m) of foam blanket, 2 inches (5 cm) thick and 36 inches (90 cm) wide, to be laid down in half an hour.

RESULTS

General Characteristics of Stable Foams

The highly expanded foam generated by compressed or blown air from water-diluted protein hydrolysate was extruded from the nozzle as a thick white band (Figure 1) that resembled shaving lather in consistency and appearance. It was soft in texture and flowed easily as it emerged from the nozzle, but immediately acquired rigidity and an astonishing degree of structural strength. Although the foam could be penetrated easily with a finger or a pointed tool, large pieces of it could be broken off, lifted intact, and balanced in the hand without bending or fragmenting. When applied, the foam easily bridged a gap of 2 feet (60 cm) between the plants (Figure 5), and as it was very light in weight it did not greatly bend or snap off any of the shoots or leaves even of seedling tomatoes.

In these and other characteristics, foam generated by compressed air differed considerably from foam produced by machine-blown air. The variation was mostly due to the amount of pressure energy available. No comprehensive study has yet been made of all the factors that enter into the making of foams of different properties, nor have precise physical measurements of these properties been made. Our experiments were directed toward providing a most stable lightweight cover. In this respect, foams generated by the more greatly energized compressed air were consistently better. Compressed air was probably of only temporary advantage, because mechanical air-blowing devices that produce foams of desirable quality are being developed rapidly.

Features of Application and Coverage

In early experiments (6) the foam used was much less expanded, heavier, and much more fluid than the present-day product. It was directed from the end of a

rubber hose toward the base of the plant and applied until it covered the entire plant. While the insulation produced (6) was adequate, the cost involved, as well as the quantity of foam used and the time needed for application, meant that such application was simply prohibitive. The foam used in the experiments reported here has properties of high expansion and stability, which permits the formation of a canopy draped over the entire plant and a blanket of insulation continuous in the row. In our tests, the peripheral parts of the plants touched the foam and, if viewed in cross-section, the canopy resembled a tunnel. It was evident from the beginning that a single design of applicator or nozzle would not serve all plants or purposes because of different plant or row configurations and different insulation requirements. Consequently, various types of canopy were spread, mainly by modifying the shape or contour of the nozzle orifice for manual applications and by variously combining and arranging a number of such nozzles attached to the tractor trailer when application was by machine.

For manual application to small plantings, it was found convenient to use a fan-shaped nozzle of comparatively small dimensions. This nozzle spread a single band of foam 2 to 3 inches (5 to 7.5 cm) thick and 20 inches (50 cm) wide (Figure 1). Complete coverage of wide row plantings was achieved by running the band back and forth two or three times along the row until a continuous canopy was formed. The use of multiple bands of foam (Figure 2) to cover wide rows was found suitable for machine applications to large plantings as well, but the operation was speeded up by applying two or three bands simultaneously from a bank of two or three nozzles fitted at the rear of or to the sides of the tractor trailer (Figure 4). The nozzles were separately adjustable to different heights and degrees of overlap of foam. The method provided flexibility and adaptability to requirements of shape and height demanded by the plant and to modified requirements as the plants grew in height and breadth. A typical coverage made in this way is shown in Figure 4.

In the first experiments, improper arrangement of the nozzles and foams accounted for the rough expansion of the cover, which is noticeable in Figure 4. However, experience easily amended this undesirable feature. More serious was the problem of covering tomatoes that were somewhat advanced in growth. The gaps between plants and the rigid protruding stems prevented the formation of a continuous canopy. Fairly large seedlings will probably seldom need such complete protection, and once tomato plants have matured and spread out, their substantial leaf surface will provide a suitable base. Such a broad surface is essential for laying a good mass of foam. Coverage for both young seedling tomatoes in spring and mature tomatoes in fall, as well as low-lying plants like strawberries, presents no difficulty. Open-branched fruit trees and shrubs, however, because they give inadequate mechanical support for a continuous canopy of foam, still present a definite problem. For machine application, adjustment of the flexible nozzle assured smooth application of foam even on mature tomato seedlings (Figures 6 and 7). The application itself, with overlapping ribbons of foam emerging, enveloping each plant in turn, and forming a continuous canopy as the tractor and

trailer progressed between the rows, was an impressive sight. Such smooth canopies of foam withstood wind velocities up to 15 mph (24 km/hr).

Another type of application well suited to the covering of wide strawberry plantings was made with the first tractor trailer that we used in our experiments, and for it we utilized a single crescent-shaped nozzle wide enough to span the breadth of the row. This nozzle, drawn from the rear of the trailer and suspended vertically over the plants, laid down a single broad ribbon of foam that completely blanketed the row in one pass (Figure 3). The curved shape of the nozzle conformed so completely to the shape of the plantings that no gaps were left on the edges. The advantage of a single nozzle applicator of this kind is that, once constructed, little further modification or adjustment is necessary and it may be used permanently for application to mature strawberry plantings.

With increased use of foam for frost protection, new and modified designs of applicators will undoubtedly be developed. The design of a suitable nozzle is manifestly an important factor in achieving efficient coverage. The speed of movement of the trailer and the properties and rate of generation of foam also need further consideration. It was often found that when the tractor moved above a certain speed, breaks in the canopy of foam occurred as the nozzle advanced. The generation and rate of delivery of foam, then, will have to vary with the rate of travel of the trailer, and as application on larger areas becomes more in demand, the speed of foam generation and delivery will also have to increase.

Stability

The most advantageous feature of the foam developed in 1967 was its stability. Without this property our experiments could not have yielded successful results. Whether generated by compressed air or by air blower, this newly formulated foam persisted for at least 18 hours after application and often for 24 hours in favorable weather. This long duration of stability meant that foam could be applied as early as the afternoon of the day preceding a predicted overnight frost and be effective throughout the night and even during the following morning.

The foam was not only stable for the time it was needed, but it disintegrated and dispersed spontaneously after the necessary period of frost protection was over, and the plants then resumed normal photosynthesis and growth. Instability and collapse of most liquid foam is usually caused by loss of water. The cooperating company had chemically modified existing fire-extinguishing foam so that this drainage was prevented or restricted by comparatively slow drying, and the foam retained structure and stability for a longer time. When the foam dried out, it soon disintegrated and dispersed. The unique feature of this foam was the balance of high-stability characteristics and spontaneous destructibility. The antagonistic properties of the foam reacted intrinsically to protect the plant during a spring overnight frost. Frost usually occurs when there is little or no sunlight or wind, and

temperatures are low. These conditions prevent drying out or destruction of the foam for the required period of protection against frost. However, the next morning, strong sunlight and high temperatures rapidly evaporate and disintegrate the foam, and restore the uncovered plants to normal conditions necessary for growth and photosynthesis.

The previously mentioned conditions are ideal circumstances for a spring frost. But when these conditions vary, the stability and the persistence of the foam change accordingly. Therefore, if calm, cool days follow a frost, the foam will persist and thereby limit growth. Heavy rain preceding a frost could wash away the protective foam, which is easily dispersed with water. Wind also hastens dispersal. Both wind and rain are a disadvantage before a frost, but an advantage afterward. However, as mentioned previously, a properly laid canopy can withstand wind as high as 15 mph (24 km/hr).

For extended protection, a foam with greater stability than those mentioned in this publication can be manufactured. When there is a risk of two consecutive nights of frost, a 48-hour protective foam would be economical, but the effects on the growth of plants during the intervening day must be considered. A plant cover of protracted duration could lead to some cumulative starvation of plants. The climate and type of plants must be considered when the kind of foam to be used is chosen.

Figures 3, 4, 7, 8, 9, and 10 show some of the remarkable properties of stability and self-destruction of the new foam. Figure 4 shows an uneven machine application to large seedlings of tomatoes made in the afternoon. Figure 8 shows healthy tomato plants breaking through the disintegrating foam the morning after a frost. Figure 7 shows a close-up of part of a smooth canopy of foam (Figure 6) applied to the same tomatoes a few weeks later. Figure 7 was photographed in the afternoon, when the foam was applied. Figure 9 shows the same foam the next morning after a frost when temperatures remained low. In Figure 9 the foam is drying and cracking, but the tomato plants have not yet broken through. Figure 3 shows strawberries with foam applied by a machine with a single wide applicator on the afternoon of a late spring day. Figure 10 shows the foam cracking on the morning after the application, but most of it still almost intact.

Insulation and Protection

1967 manual experiments – In the early morning of October 7, 1967, when the first frost of the autumn occurred, tests proved that canopy covers made from the new stable foam could be used satisfactorily for insulation against frost. At that time, neither mobile equipment nor power-driven air blowers had yet been developed, so the foam had to be generated by compressed air with the improvised stationary equipment described previously and then applied manually with a fire hose from the generator to the nozzle. The plants were mature tomatoes laden with

ripe and unripe fruit in 50-foot (15-m) rows. They were covered with multiple ribbons of foam about 2 to 3 inches (5 to 7.5 cm) thick and 20 inches (50 cm) wide (Figure 2). Only alternate rows were covered; the uncovered rows served as controls. The weather in September and early October had been mild, sunny, and free from frost. All the tomato plants and fruit were healthy, so surviving and nonsurviving plants in covered and uncovered rows were easily detected. The insulative properties of the foam were calculated from temperature recordings and from visual and photographic appraisals of survival. The contrast between the covered and the uncovered plants was so sharp that only the results of the temperature recordings need to be given here. (To show the insulating capacities of the foam, graphs of the temperature recordings taken after two foam applications made by machine in 1968 during a typical light frost and a severe frost are given in Figures 13 and 14.)

In the test in October 1967, the foam was applied (Figure 5) at about 3 to 4 p.m. on the day preceding the frost. During the night and the following morning, the air temperature outside the foam, 5 inches (12.5 cm) above the soil, was never above the freezing point for at least 7 hours, and even dropped at 3 a.m. to 25°F (-4°C), the lowest temperature for that day. However, the temperature under the foam at this time was 38°F (+3°C), and it never fell below freezing.

The appearance of the tomato plants the following morning, after the foam had been washed off, confirmed the temperature records. All the tomato plants that had been left uncovered (Figure 11, *right*) were killed or injured, whereas the plants that had been under the blanket of foam (Figure 11, *left*) showed no traces of damage. Also, every fruit in the uncovered rows (Figure 12, *left*) showed blemishes, but those in the covered rows (Figure 12, *right*) were free of such blemishes. Several days were allowed to elapse, then the plants that had been covered with foam were examined for the presence of any residual or latent injury. No change was observed; the tomatoes protected during the frost still showed vigor, but, in the exposed rows, leaves were blackening and drying and the fruit was rotting.

Because the results of these tests were so promising, the decision was made to explore and develop mobile machines for generating and applying foam on a large scale. The insulating capacities of foams generated from compressed air were now fully established, but foams applied by machine had not been tested for insulating value. Mobile machines that generated and applied foam were available by May 1968, but they were not tested under frost conditions until October 1968. During that month, many tests were performed but only two, one made during a light frost and the other during a severe frost, are reported here. In these tests visual and photographic survival was not appraised. Because tomatoes succumb to the slightest frost, the severity of a frost and the degree of protection afforded by a foam cover cannot be ascertained only from the frost damage to the control rows of tomatoes. In addition, continuous temperature records were made throughout the frost, and

these records were used to calculate the true insulation potential of machine-applied foam.

1968 machine experiments — Tests were performed on tomato seedlings, about 18 to 20 inches (45 to 50 cm) high, that had been set out in September. The plants were thoroughly blanketed with a canopy layer of foam 2 to 3 inches (5 to 7.5 cm) thick, which was applied from three overlapping nozzles fitted to the tractor-drawn trailer. Temperature readings were made with shielded copper—constantan thermocouples connected to a battery-operated recording potentiometer and located at different levels underneath and outside the foam. Temperatures were recorded at 15-minute intervals near the tomato plants at the surface of the soil and 3 inches (7.5 cm) above the soil in the air underneath the foam (Figures 13A, 13B, 14A, 14B). Temperatures were also recorded for the air on the surface of the foam and at 36 inches (90 cm) above the ground (Figures 13C, 14C). The four readings each hour were averaged and these values were plotted in the graphs (Figures 13 and 14).

Figures 13A, 13B, and 13C show the temperature variations recorded during a light overnight frost on October 5. The length of time that temperatures of 32°F (0°C) or higher were maintained under the foam at different levels compared with the length of time the air temperatures were below freezing (shown by stippled areas in Figures 13 and 14) indicates the degree of protection afforded at the different levels. The temperature plots in Figure 13 show that air temperatures, although not freezing, were rather low when the foams were applied, somewhat higher towards midnight, then suddenly lower about 2 a.m. The temperature dropped when a heavy cloud cover, which had prevailed till 2 a.m., suddenly cleared. The temperature dropped below freezing for about 4 hours at all levels in the air and at the surface of the foam (stippled areas in Figure 13). All uncovered tomato plants were killed by this frost. The temperatures in the foam provided a striking contrast (Figures 13 and 14). The sudden radiative cooling of the air only slightly affected the temperature under the foam, where temperatures at the surface and at 3 inches (7.5 cm) above the ground dropped somewhat but never approached freezing (Figures 13A, 13B). All covered tomatoes survived.

The temperatures under the foam were higher from the start because of heat trapped in the air bubbles during generation of the foam. Nevertheless, this heat could not account for the increased differential that developed between air temperatures and temperatures underneath the foam after 2 a.m. (Figures 13A, 13B). At one point this differential amounted to about 20°F (11°C) at the surface of the soil (Figure 13A). Only insulation by the foam could have accounted for such a differential. Also, temperatures recorded in further tests showed that even where temperatures were nearly the same in the air and under the foams at time of application, this widening differential continued to develop. It is certain that the incorporation of warmer air into the air bubbles during generation of the foam or use of warmer solution would augment the protective effects of the insulation. The

foam is effective as insulation partly because the trapped air bubbles act as a barrier and prevent loss of heat by the plant. Protection is also obtained by the resistance that the blanket of foam offers to the loss of heat from the ground through radiation.

The insulation used to protect the tomatoes from the light frost in the test on October 5 was far thicker than was needed. A severe frost on October 31 provided the opportunity for a more rigorous test of insulation. The temperatures were recorded near large seedlings of tomato plants that were now barely alive because they had been almost constantly covered with foam to protect them from the cool temperatures and frequent frosts that month. For this reason the plants did not survive after the test, but the foam cover during the severe frost prevented them from being completely killed. The graphs of recorded temperatures show the extended duration and severity of the freezing temperatures in the air at various levels above the ground in the vicinity of the foam cover.

Air temperatures of 25°F (-4°C) or lower lasted 6 to 8 hours, depending on the level at which the readings were taken. It is remarkable that the temperature under the foam, at the surface or 3 inches above the soil, did not reach the freezing point. This is illustrated strikingly on the graphs (Figure 14) by the complete absence of stippling under the foam temperature plots. The large differential between temperatures under the foam and outside was entirely due to the insulative effect, because the temperatures in the foam at the time of application did not differ greatly from the air temperatures.

Such a clear demonstration of insulating capacity had not been obtained previously. In most places in the canopy, the foam was nearly 3 inches (7.5 cm) thick. The foam plot in Figure 14B shows that less insulation would have brought the plants dangerously close to freezing under the severe conditions of the test. In this plot, the blanket of foam at the thermocouple junction was about 1 inch (2.5 cm) thick. Further studies with foams of various thicknesses should determine the thickness of foam required for each kind of frost condition.

The 1968 tests proved that foam generated by an air blower and applied by mobile equipment gave as good a cover and as complete an insulation as foam generated from compressed air and applied by hand.

Lack of Toxicity

Seedling tomato leaves and fruit, and the possibility of early spring planting — The complete survival of the covered tomato plants and fruit in the October 1967 frost tests and the continuing vitality of the plants showed that no immediate or latent toxic effects of the foam or the foam cover had occurred. No toxicity was observed even where the foam canopy wet the terminal shoots or leaves. The survival of seedling tomatoes during the prolonged and repeated applications of

foam for insulation tests during October 1968 also proved the harmlessness of the foam. The fresh appearance of tomatoes breaking through disintegrating foam (Figure 8) the morning after one of the numerous frost tests illustrates vividly with what impunity tomatoes were able to tolerate the repeated applications. Because the foam contains nitrogen, it also shows some fertilizer effects (3).

Tests designed to explore the possibility of very early spring planting of tomatoes gave a better indication of the lack of toxicity of the foam. Rows of tomato seedlings, which are planted in the Ottawa area usually at the end of May, were set out instead on May 7. For trial runs of machine applications of foam and for protection against frost, these seedlings were blanketed overnight with foam five times during May. However, there was no frost and the temperatures were unusually mild. These conditions should have accentuated any toxic effects of the foam. But growth was not impaired and by the end of May, when the seedlings were usually planted, the early plantings were very much farther advanced. The contrast between the early and the normal plantings is shown in Figure 15, photographed on June 19. Fruit from the early plants was ripe for picking on August 12. To serve as controls, some of the early plantings had not been covered with foam. There was no significant difference in yield of fruit from covered or from uncovered rows; 36.8 pounds (16.7 kg) of tomatoes were gathered from a row of plants that had been covered, and 37.4 pounds (17 kg) from a similar row that had not been covered.

Strawberry leaves and blossoms undamaged – The most spectacular demonstration of a lack of toxicity of the foam was obtained in experiments on two mature rows of strawberry plantings. Before and during blossoming and for some time after, in late May and early June, eight applications of foam, similar to that shown in Figure 5 and each lasting overnight, were made on half of each row of strawberry plants. The other half of the row was left as a control. The covered half was completely blanketed at each application, as shown in Figure 6. Nevertheless, the next morning, when the foam cracked as it disintegrated, blossoms and leaves showed no signs of injury (Figure 10). Because the canopy of foam was supported mostly by the leaves, some, but not many, of the blossoms had been wet by foam. Even the blossoms that had been wet showed no damage. Then bees were observed passing through the cracks of the foam. It seemed that pollination and fruiting would proceed normally. This was confirmed strikingly when fruit appeared in the previously covered rows on June 17, and continued to ripen until June 25. For some days, the yield of fruit was as high in the part of the rows that had been covered repeatedly as it was in the uncovered rows. The cumulative yield of fruit, in grams, from several gatherings made at this time in covered and uncovered sections of the rows shows:

	Row 1	Row 2
Foamed half	5,151	8,625
Normal half	4,638	9,743
(not foamed)		

Initially, the fruit in covered rows was just as large and healthy as that in uncovered rows. But, later, the yields dropped off somewhat and the fruit began to look a little distorted. This is not surprising because the covered strawberries, while still in blossom and early fruit, had been under foam canopies at least four times for periods of at least 18 hours. It is remarkable, then, that more damage was not observed.

Lack of Toxicity to Man

Although little residue remains on the plant after the foam disintegrates because of its high dilution, the possibility that the lingering or scattered residue on fruit of tomatoes or strawberries might be toxic to man had to be examined. The precise composition of the foam concentrate has been made known to the Food and Drug Directorate of the Department of National Health and Welfare, and the foam has been approved by them for application to vegetable and fruit crops.

Marketability of Crops

The possibility of foam residue discoloring fruit or vegetables has also been considered. Because of the great dilution, there is little probability of residue of significant proportions contaminating these fruits or vegetables. Also, the foam is applied as a canopy and is carried mostly by the leaves of tomatoes or strawberries. It is conceivable that foam residue might linger on leaves and then scatter to the fruit, but this residue can be washed off easily. When covering is applied only at the blossoming or leafing stage of a plant, this possibility never occurs.

CONCLUSIONS

The results of the investigations reported here show that a protein-based foam can be produced that fulfills all the requirements of stability, insulation, ease of application, lack of toxicity, and capacity for spontaneous disintegration that could conceivably be demanded of an ideal temporary cover for protecting plants against frost. The results also show that the foam can be generated with equal facility from compressed air or from mechanically driven air blowers and can be applied manually and, more speedily, by machine, according to the dimensions of the crop that has to be protected. Frost protection with this foam, therefore, appears to be practical. What is needed now for the further development of this important application of foam is extension of the scope of the testing operations to include as many experimental stations or commercial establishments as possible so that the engineering and economic aspects can be thoroughly worked out. The foam product is commercially available now, so independent trials by growers and farmers are possible.

While the results contained in this paper were being prepared for publication, continued modification and improvement by the cooperating company of the

design and construction of the prototype mobile machine applicators described above has proceeded. A number of highly efficient mobile units of various dimensions and capacities are already available for use in trials on both small and large acreages. The new units are capable of applying blankets of foam of every conceivable variety and dimension and with much greater precision, speed, and uniformity than was hitherto possible with the units described and used in the present experiments. The cooperating company anticipates that such units will soon come into larger commercial production and that literature describing the use and operation of these units will be available at the same time.

As a result of a preliminary press announcement of the results that are given in this paper, correspondence and requests for information and materials indicate that there is much interest in the use of stable foam for frost protection. Large-scale tests and trials of the foam with these new units in frost-prone areas is expected. It is hoped that the use of foams will be extended for the protection of other crops such as tobacco, melons, peppers, cranberries, blueberries, and even grapes. Possibilities for protection of open-branched tree fruit crops such as apples and peaches seem more remote, because these trees cannot support and maintain a continuous canopy of foam. However, it is still possible that citrus trees, which grow under more crowded conditions, may be cultivated to hold such a canopy.

Several other areas of investigation in the use of foams should be studied in these extended tests. For example, no comprehensive measurements have been made of the insulation variation with thickness of foam canopy. Chesness and his colleagues have made a series of such studies with their own foam formulations (2). Similar studies with protein-based foams are needed, because the thickness of the foam affects the cost of application. From such insulation and meteorological data, which indicate the degree of stress to be expected, it should be possible to determine the thickness and cost of an adequate foam blanket for the crop that is to be protected. Therefore, the severity and frequency of the frost and the value of the crop will dictate the requirements and feasibility of foam protection.

The most economic use of foam protection depends upon precise meteorological methods that accurately forecast the time of incidence and severity of frost. Previously, such forecasts were of limited value, because little could be done to protect large plantings from frost. The method of frost protection provided by foams would be more accurate if frost prediction were based on computer analysis of meteorological data.

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Figure 1. Manual application of foam to mature tomato plants.



Figure 2. Multiple bands of foam applied to alternate rows of tomato plants from a stationary unit.



Figure 3. Application of foam by mobile unit of 200-gallon (900-litre) capacity to rows of flowering strawberry plants.



Figure 4. Foam application on tomatoes by tractor-drawn and driven unit of 400-gallon (1,800-litre) capacity.



Figure 5. Bridge of foam, applied manually, across supporting tomato plants.



Figure 6. Smooth foam application on rows of tomato plants by mobile unit.

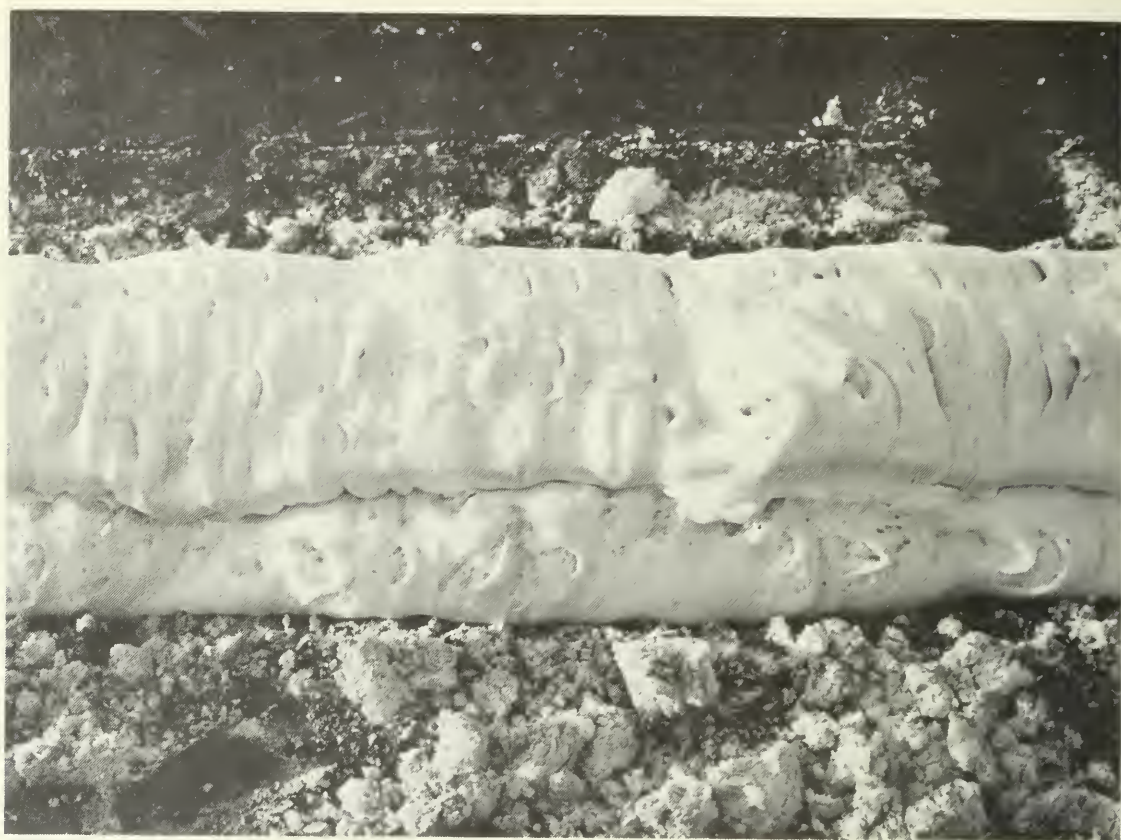


Figure 7. Close-up of smooth application of foam to tomato plants by mobile unit.



Figure 8. Tomato plants breaking through dispersing foam, about 24 hours after application.



Figure 9. Appearance of foam cover about 18 hours after application.



Figure 10. Surviving healthy strawberry plants and blooms breaking through foam 20 hours after application.



Figure 11. (Left) Surviving plants in previously covered row of tomatoes, and (right) killed and injured plants in uncovered row.



Figure 12. (Left) Frost-damaged unripened tomatoes selected at random from uncovered rows, and (right) intact unripened tomatoes from covered rows.

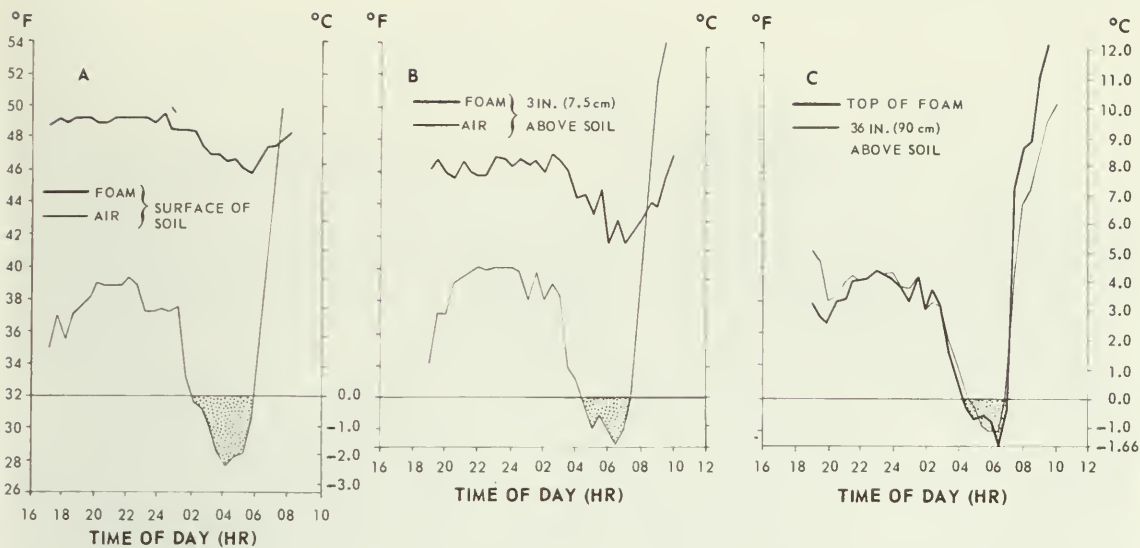


Figure 13. Temperature variation (in degrees F and C) during a period of light frost on October 5, 1968: A, underneath the foam and in air at the surface of the soil; B, underneath the foam and in air 3 inches (7.5 cm) above the soil; C, in air at the top of the foam and at 36 inches (90 cm) above the soil.

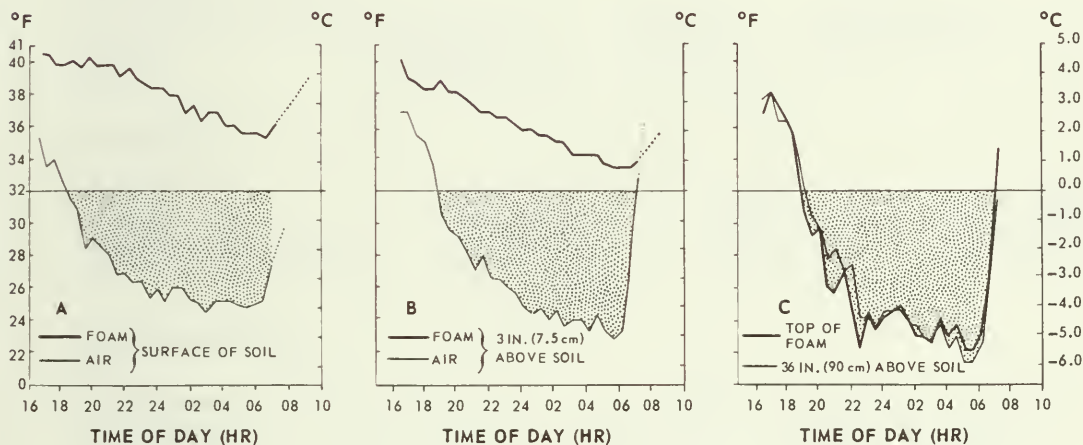


Figure 14. Temperature variation (in degrees F and C) during a period of heavy frost on October 31, 1968: A, underneath the foam and in air at the surface of the soil; B, underneath the foam and in air, both at 3 inches (7.5 cm) above the soil; C, in air at the top of the foam and at 36 inches (90 cm) above the soil.



Figure 15. Additional advantage of foam shown in growth achieved by (right) early planting (May 7, 1968) as compared with (left) regular planting (May 27, 1968) of tomatoes.



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METRIC EQUIVALENTS

LENGTH

inch = 2.54 cm	millimetre = 0.039 in.
foot = 0.3048 m	centimetre = 0.394 in.
yard = 0.914 m	decimetre = 3.937 in.
mile = 1.609 km	metre = 3.28 ft
	kilometre = 0.621 mile

AREA

square inch = 6.452 cm ²	cm ² = 0.155 sq in.
square foot = 0.093 m ²	m ² = 1.196 sq yd
square yard = 0.836 m ²	km ² = 0.386 sq mile
square mile = 2.59 km ²	ha = 2.471 acres
acre = 0.405 ha	

VOLUME (dry)

cubic inch = 16.387 cm ³	cm ³ = 0.061 cu in.
cubic foot = 0.028 m ³	m ³ = 31.338 cu ft
cubic yard = 0.765 m ³	hectolitre = 2.8 bu
bushel = 36.368 litres	m ³ = 1.308 cu yd
board foot = 0.0024 m ³	

VOLUME (liquid)

fluid ounce (Imp) = 28.412 ml	litre = 35.2 fluid oz
pint = 0.568 litre	hectolitre = 26.418 gal
gallon = 4.546 litres	

WEIGHT

ounce = 28.349 g	gram = 0.035 oz avdp
pound = 453.592 g	kilogram = 2.205 lb avdp
hundredweight (Imp) = 45.359 kg	tonne = 1.102 short ton
ton = 0.907 tonne	

PROPORTION

1 gal/acre = 11.232 litres/ha	1 litre/ha = 14.24 fluid oz/acre
1 lb/acre = 1.120 kg/ha	1 kg/ha = 14.5 oz avdp/acre
1 lb/sq in. = 0.0702 kg/cm ²	1 kg/cm ² = 14.227 lb/sq in.
1 bu/acre = 0.898 hl/ha	1 hl/ha = 1.112 bu/acre

